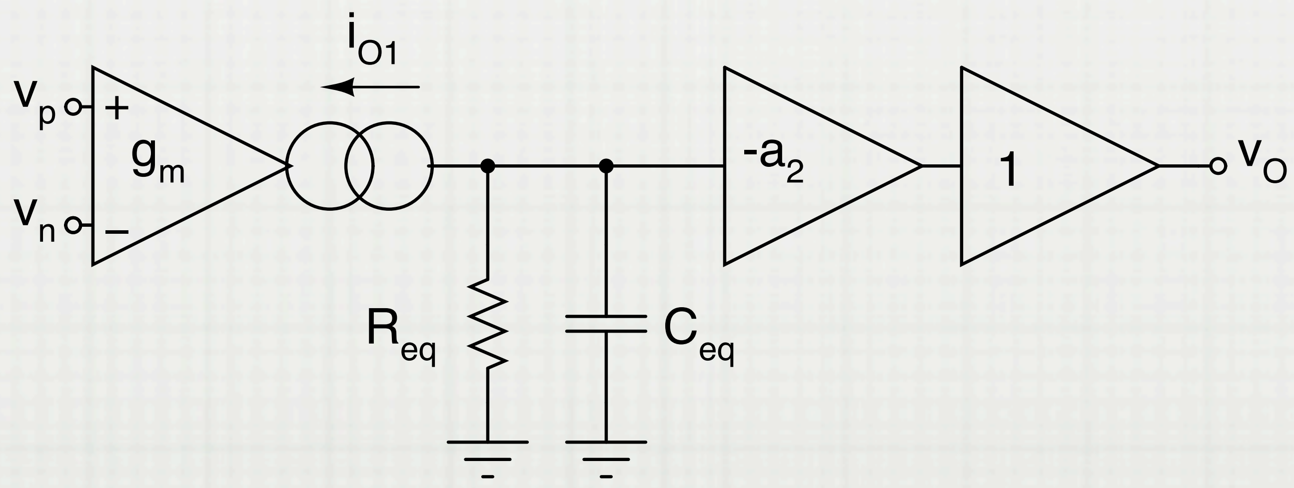
BANDWIDTH & SLEW-RATE

INEL 5207 - SPRING 2011

Frequency Limits

- Many opamps are internally compensated to have a single dominant pole at a relatively low frequency.



Noninverting Amplifier

- Open-loop gain can be wrien as:

$$a(s) = a_0 \frac{1}{1 + s/\omega_p}$$

a_0 = d.c. open-loop gain; $f_p = \frac{1}{2\pi R_{eq} C_{eq}}$ = pole freq.

- For the non-inverting amplifier

$$A = \frac{a}{1 + a\beta}$$

where $\beta = \frac{R_1}{R_1 + R_2}$.

- Using above $a(s)$ and $A_0 = \frac{a_0}{1 + \beta a_0}$,

$$A(s) = \frac{a(s)}{1 + a(s)\beta} = A_0 \frac{\omega_p (1 + \beta a_0)}{s + \omega_p (1 + \beta a_0)}$$

- Corner frequency is increased by $1 + \beta a_0$. Gain is decreased by the same factor.

- Gain-bandwidth product remains constant and equal to unity gain frequency, f_t.

$$GBP = f_t$$

- This is only true for β constant and compensated opamp (dominant pole at low freq.)

Gain of n identical noninverting stages

- If $f_{cl} = \omega_p(1 + \beta a_0)/2\pi$, then gain magnitude of one stage is

$$A = A_0 \frac{1}{\sqrt{1 + (f/f_{cl})^2}}$$

- Gain of n identical stages is

$$A^n = A_0^n \left(1 + (f/f_{cl})^2\right)^{-n/2}$$

- At corner frequency f_{3dB}, $A^n/A_0^n = 1/\sqrt{2}$ (i.e. -3dB). Thus,

$$f_{3dB} = f_{cl}\sqrt{2^{1/n} - 1} = \frac{f_t}{A_0}\sqrt{2^{1/n} - 1}$$

- To design an amplifier with bandwidth f_{bw} and gain K, we must select n such that $K = A_0^n$ and $f_{bw} \leq \frac{f_t}{A_0}\sqrt{\frac{1}{2^n} - 1}$.

Inverting Amplifier

- Bw: $f_t \frac{R_1}{R_1+R_2}$; same than non-inv with gain $1 + {}^{R_2}/_{R_1}$

- $A = A_{ideal} \frac{1}{1+{}^1/_T}$; $A_{ideal} = -\frac{R_2}{R_1}$; $T = a\beta_{non-inv}$

- For the inverting amplifier, the gain-bandwidth product is equal to

$$GBP = f_t \frac{R_2}{R_1 + R_2}$$

so the bandwidth is always lower than that of a non-inverting amplifier with the same gain.

- Equivalently, we can say that $f_{bw} \times (1 + \frac{R_2}{R_1})$ is still constant and equal to f_t, but the the amplifier's gain magnitude of is only $\frac{R_2}{R_1}$.

SLEW RATE

TRANSIENT RESPONSE

- FOLLOWER (NON-INVERTING WITH UNITY GAIN)
  - FREQUENCY RESPONSE

$$A = \frac{1}{1 + j\frac{1}{f_t}}$$

  - STEP RESPONSE

$$v_O = V_m\left(1 - \exp\left(-t/\tau\right)\right) \qquad \tau = \frac{1}{2\pi f_t}$$

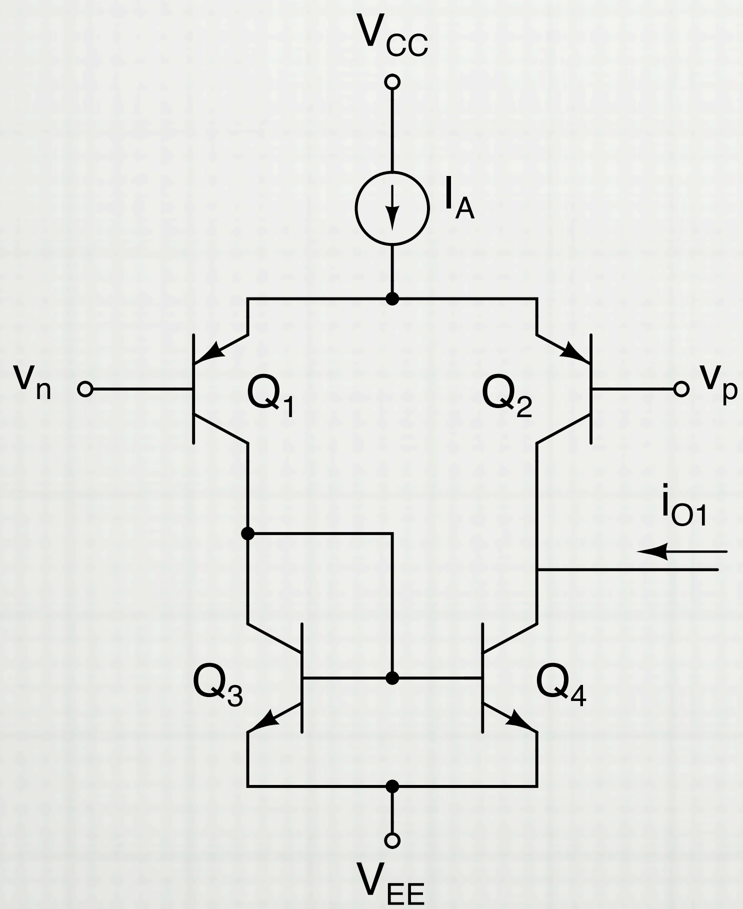
  - RISE TIME (TIME TO GO FROM 10% TO 90% OF V_M)

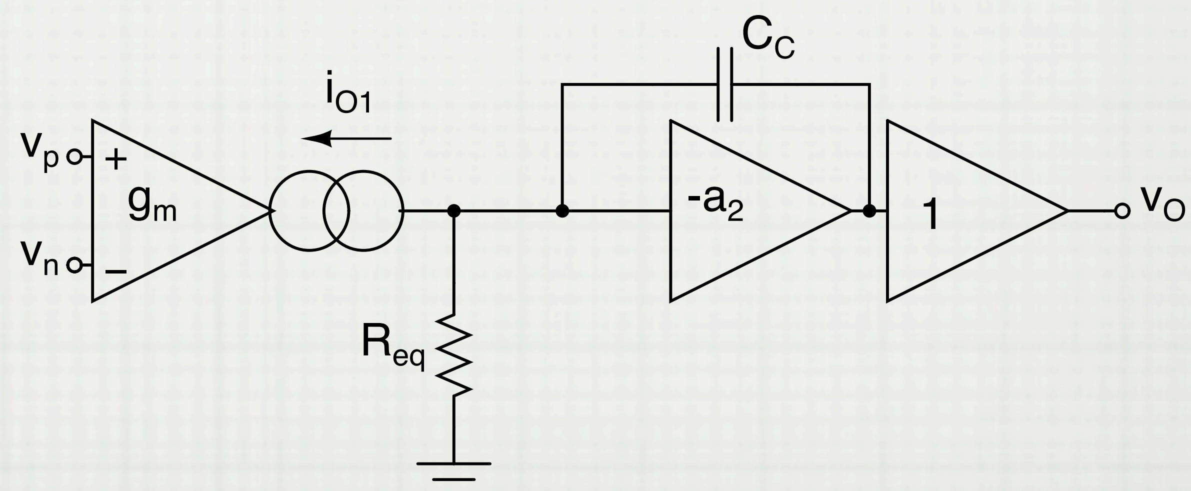
$$t_r = \frac{0.35}{f_t}$$

CURRENT STARVING

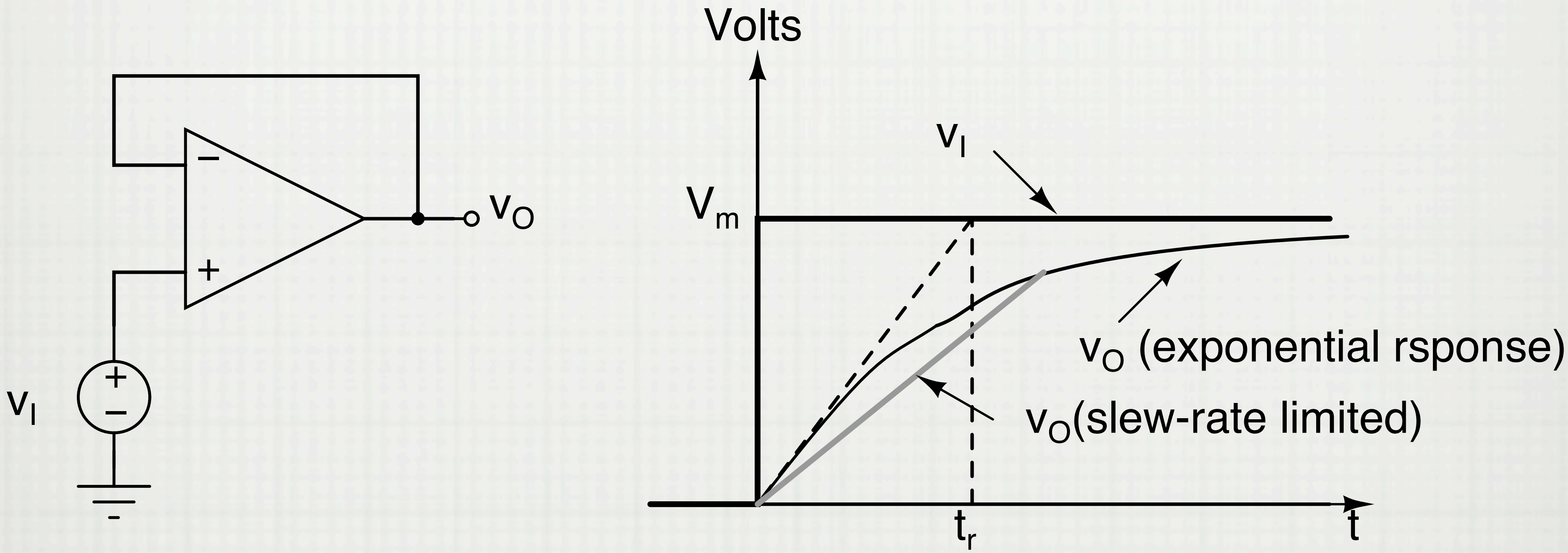
i_{O1} is limited to $\pm I_A$. Output can not change faster than

$$SR = \frac{I_A}{C_C}$$

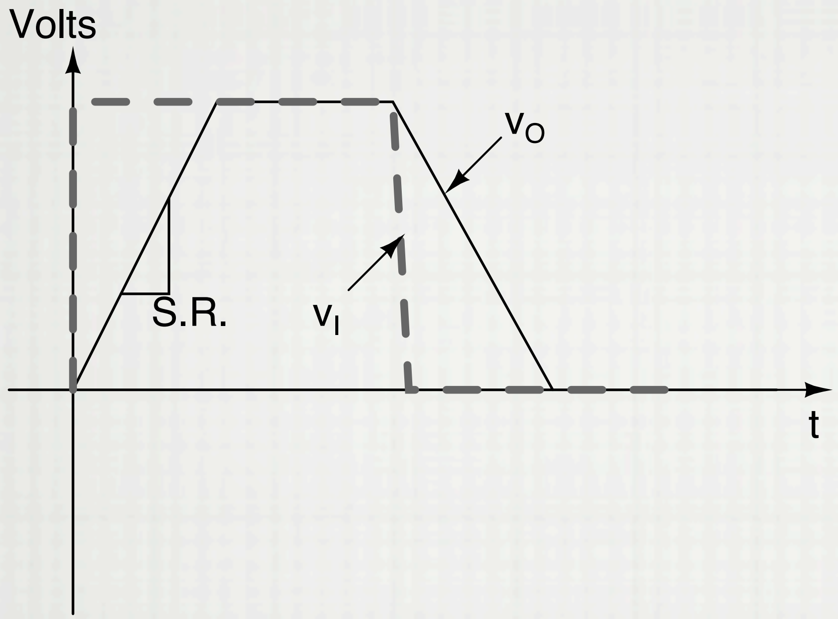


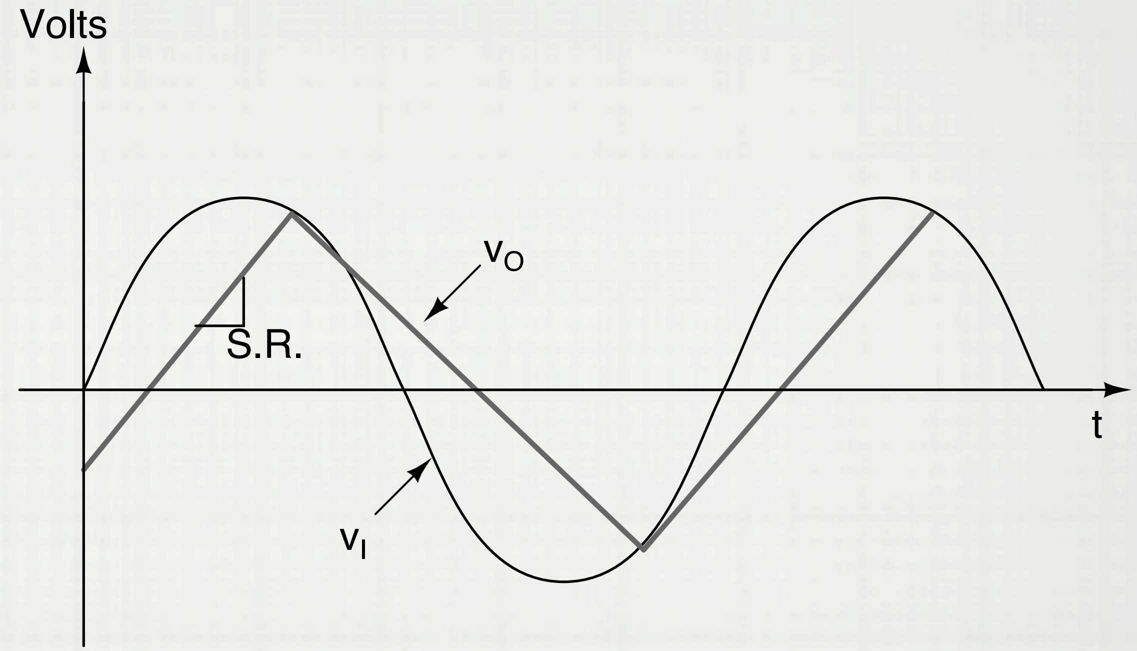


EXPONENTIAL & SLEW-RATE LIMITED STEP RESPONSE



HIGHER-ORDER POLES WOULD INTRODUCE "RINGING" - I.E. SMALL OSCILLATIONS ON RESPONSE





- Expected output: $v_{O,expected} = Av_I$
- If $\boxed{\frac{dv_{O,expected}}{dt} > S.R.}$ then $\boxed{\frac{dv_O}{dt} = S.R.}$
- If $\boxed{\frac{dv_{O,expected}}{dt} \leq S.R.}$ then the response is exponential.

For an input step, the critical output size $V_{om,crit}$ beyond which the output becomes slew-rate limited, is

$$\begin{aligned} v_{O,expected} &= V_{om}\left(1 - \exp\left(-1/\tau\right)\right) \\ \frac{dv_{O,max}}{dt} &= \frac{V_{om(crit)}}{\tau} = S.R. \\ V_{om(crit)} &= \tau \times S.R. = \boxed{\frac{S.R.}{2\pi f_B}} \end{aligned}$$

where $\boxed{\tau = \frac{1}{2\pi f_B}}$, f_B is the closed-loop bandwidth i.e.

- $f_B = f_t$ for unity gain,
- $f_B = \beta f_t$ for non-unity gain, where β is the non-inverting amplifier feedback factor.
- $V_{om} = \mid A \mid \times V_{im}$ where V_{im} is the size of the input step and A is the (inverting or non-inverting) amplifier gain

When the input is a step and $V_{om} > V_{om(crit)}$,

- initially v_O changes linearly

$$v_O(t) = SR \times t \ \forall \ t < t_1$$

- for $t > t_1$ where t_1 is defined by

$$V_{om} - v_O(t_1) < V_{om(crit)}$$

the output changes back to a linear response and.

$$V_O(t) = V_{om} - (V_{om} - v_O(t_1)) \exp^{-(t-t_1)/\tau}$$

For an <u>input sinusoid</u>,

- non-slew-rate limited output signal $v_O = V_{om} \sin 2\pi f t$
- v_O rate of change would be $\frac{dv_O}{dt} = 2\pi f V_{om} cos 2\pi f t$
- maximum rate of change is at $t = 0$, $\left(\frac{dv_O}{dt}\right)_{max} = 2\pi f V_{om}$
- for $V_{om} \geq V_{om,crit}$, the output becomes *slew-rate limited*,

$$2\pi f V_{om,crit} = S.R.$$

or

$$\boxed{V_{om(crit)} = \frac{S.R.}{2\pi f}}$$

- Observe that $V_{om} =\mid A \mid \times V_{im}$ where V_{im} is the input signal peak and A is the amplifier gain.

Given desired V_{om} we find the maximum frequency of sinusoid with undistorted output:

$$f_{max} = \frac{SR}{2\pi V_{om}}$$

<u>Full-power bandwidth (FPB)</u>

Maximum frequency for which the opamp output is undistorted sinusoid with the largest possible amplitude. If saturation voltage is $\pm V_{sat}$

$$\boxed{FPB = \frac{SR}{2\pi V_{sat}}}$$